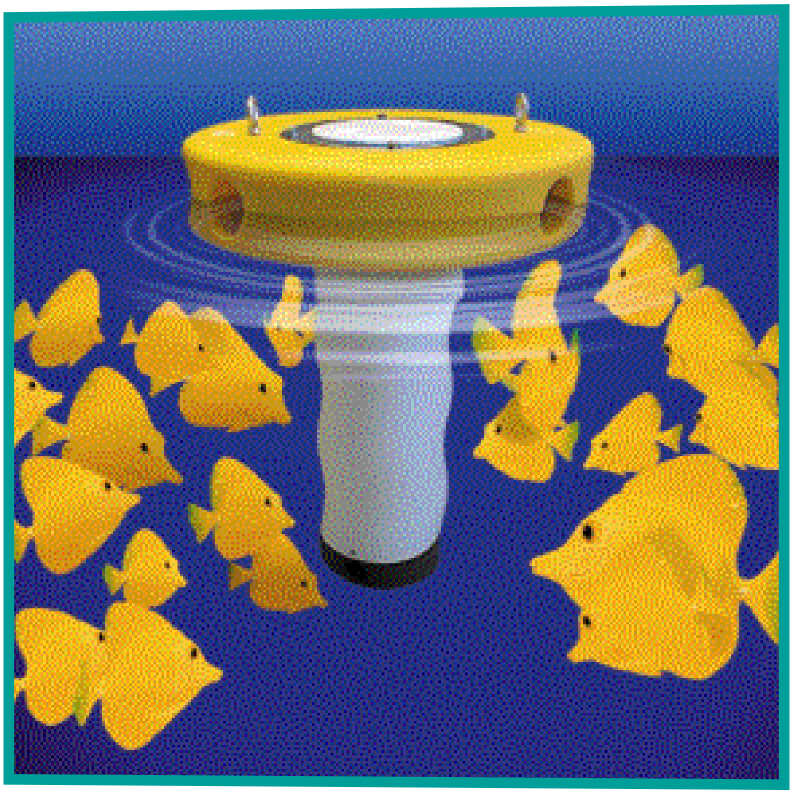
ESTCP
Cost and Performance Report

(SI-0002)



Demonstration of an Automated Oil Spill Detection System

July 2008

ENVIRONMENTAL SECURITY
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ACRONYMS AND ABBREVIATIONS

AML	Applied Microsystems, Ltd.
bbl	barrel
DoD	Department of Defense
ESTCP	Environmental Security Technology Certification Program
FCC	Federal Communications Commission
FISC	Fleet Industrial Supply Center
FM	frequency modulation
ft	feet
gal	gallon
ml	milliliter
mo	month
MHz	megahertz
NRDA	Natural Resource Damage Assessment
OSOT	Oil Spill On-site Team
POL	petroleum, oils, and lubricants
PSNSY	Puget Sound Naval Shipyard
QA/QC	quality assurance/quality control
SPAWAR	Space and Naval Warfare Systems Command
SPAWARSYSCEN	Space and Naval Warfare Systems Center
UV	ultraviolet
yr	year

ACKNOWLEDGEMENTS

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Participants. Some of the key participants contributing to the overall success of this project include: Bill Boucher, Puget Sound Naval Shipyard; Maureen Conners, Norfolk Naval Station; Karen Barta and Lisa Swann, Langley Air Force Base; and Cynthia Pang, Chief Robinson; and the Oil Spill On-site Team (OSOT) crew at Pearl Harbor. Bill Schmidt and James Lane of the Department of the Interior's Minerals Management Service were very helpful in coordinating the testing at Ohmsett. Tom Dakin, Mike Penny, and Greg Eaton of Applied Microsystems, Ltd. have been instrumental in improving upon the original Navy prototype and redesigning it for commercial applications. Gregory Anderson of Space and Naval Warfare Systems Center (SPAWARSYSCEN) San Diego provided design expertise as the project lead engineer.

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1.0 EXECUTIVE SUMMARY

1.1 BACKGROUND

The mandatory cleanup of accidental releases of petroleum into the environment costs the Department of Defense (DoD) millions of dollars annually. DoD agencies are responsible for the cleanup of thousands of barrels (bbl) of petroleum, oils, and lubricants (POL) spilled into the marine environment each year. The total volume of accidental POL releases at Navy facilities alone has exceeded 3.4 million gallon (gal) over the past decade. Estimates of the associated economic costs, which include cleanup, disposal, lost product, and fines range from a low of $2,000/bbl to as high as $18,000/bbl. Other, noneconomic costs associated with major spill occurrences include irreversible harm to ecologically sensitive areas as well as damage to local community relations arising from a perception of negligent environmental stewardship within the DoD.

Current spill detection and response strategies rely solely on the use of human observation to visually detect the presence of a surface sheen indicative of a petroleum spill. Once an oily sheen is spotted, a response team is alerted to contend with the spill. The response team will first seek to isolate and stop the source if a leak is still occurring, then use any combination of skimmers, absorbents, and booms to contain and remove the spilled material. Early identification of a leak or spill, enabling responders to take immediate corrective action is an important means of preventing large volume releases and reducing the associated environmental damage and economic cost. Early spill identification can only be achieved through diligent continuous monitoring.

The U.S. Navy has developed an automated oil spill detection technology, *Spill Sentry*, to improve the accuracy and timeliness of spill reporting. The system detects petroleum contamination in aquatic systems with an upward-looking underwater multispectral fluorometer that is designed to float just below the water's surface. The optical system utilizes the germicidal effects of ultraviolet light to prevent biofouling, thereby enabling underwater deployment for indefinite periods of time, even in high fouling environments. Data are transferred in one of two ways: either through a hard-wired umbilical or via a wireless data link. The wireless sensors utilize a solar cell for onboard power requirements to simplify deployment.

1.2 OBJECTIVES OF THE DEMONSTRATION

The objectives of this demonstration were to test and validate *Spill Sentry* under real-world conditions and to promote rapid transition to DoD users by facilitating commercialization, user awareness, and regulatory acceptance. To meet these objectives, year-long field demonstrations were conducted at Puget Sound Naval Shipyard, Bremerton, Washington; Langley Air Force Base, Hampton, Virginia; Norfolk Naval Station, Norfolk, Virginia; and Pearl Harbor Naval Station, Pearl Harbor, Hawaii. Additionally, in order to validate the system under controlled conditions and to verify performance parameters, wave-tank testing was conducted at the Ohmsett National Oil Spill Response Test Facility in Leonardo, New Jersey. Ultimately, the goal in demonstrating the effectiveness of utilizing an automated oil spill monitoring system was to provide users with the means to eliminate the need for 100% reliance on human visual observation to detect oil spills.

1.3 REGULATORY DRIVERS

U.S. Army, Navy, and Air Force facilities are required to comply with federal, state, and local legislation relating to the control of marine and aquatic oil pollution. Federal legislation requires reporting and cleanup of any spill large enough to cause a surface sheen on the water.[1] In California, the Lempert-Keene-Seastrand Oil Spill Prevention and Response Act of 1990 requires the implementation of an oil pollution monitoring program at all marine oil transfer facilities in the state, yet no service branch to date has implemented a compliant program.[2] Demonstration of the automated oil spill monitoring/detection system also directly addresses high priority U.S. Navy/Tri-Service needs as documented in the Environmental Security Technology Requirement Guidance: (ID Number 2.V.1.x) Oil Spill Detection, Minimization, and Recovery Technology.

1.4 DEMONSTRATION RESULTS

Overall, the *Spill Sentry* met or exceeded expectations in most key performance objectives, including the ability to detect petroleum, performance in choppy seas, freedom from spectral interference, ease of use, and effective use of ultraviolet (UV) light to prevent biofouling. However, the system significantly underperformed in two critical areas: reliability and false alarm rate. Though missing demonstration objectives, the relatively high false alarm rate is not a worrying concern; it can be substantially improved by adjusting the alarm threshold to meet site conditions and user needs. The reliability of the system, as measured by uptime during the demonstrations, is a more significant shortcoming. Uptime averaged just 47% at the four demonstration sites. This is largely attributable to the uncertainty and learning involved with first time use of prototype systems. Important lessons learned during the demonstrations as well as engineering improvements made to production systems will certainly improve future performance in this area.

1.5 STAKEHOLDER/END-USER ISSUES

The *Spill Sentry* technology demonstration serves to establish user confidence in the new oil spill detection technology. This is especially important as automated spill detection represents a completely new approach to pier-side monitoring. End users had expressed initial concern over issues, including the potential for generating false positives, the importance of data security, overall ease of use, low cost, durability including the ability to withstand severe storms, and effectiveness in detecting oil. Information and network security also represents a broader user concern when linking the oil spill sensors' real-time, web-based data capability to local networks.

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[1] Clean Water Act (33 U.S.C. 1251), Oil Pollution Act of 1990 (33 U.S.C. 2701 et. seq.), Oil Pollution Prevention Regulations for Marine Oil Transfer Facilities (33 CFR 154), Discharge of Oil (40 CFR 110), Pollution Prevention Act of 1990, and Oil Spill Prevention Control and Counter Measures Planning Manual (NFESC 7-03), PNAVINST 5090.1B.

[2] California Government Code and Public Resource Code, collectively referred to as the *Lempert-Keene-Seastrand Oil Spill Prevention and Response Act*. California Government Code: *Chapter 7.4, Oil Spill Response and Contingency Planning Articles 1-10*; Public Resource Code: *Division 7.8, Oil Spill Prevention and Response, Sections 8750-8760*.

End users can now obtain *Spill Sentry* systems, system service, and support directly through Applied Microsystems, Ltd. (AML). The technology currently being marketed by AML has benefited significantly from the lessons learned from the ESTCP demonstrations. The newest generation of sensors has been significantly improved to be more durable, less expensive, and easier to deploy.

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2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY DEVELOPMENT AND APPLICATION

The *Spill Sentry* technology was originally developed by the U.S. Navy at SPAWARSYSCEN San Diego. Development of the automated oil spill detection system began in 1995 with the first prototypes being tested in 1997. Work to incorporate engineering refinements and improvements continue into the present. The basic technology is protected by U.S. Patent US05929453, Underwater Multispectral Fluorometer, issued in January 2000. The Navy has licensed exclusive worldwide rights to commercialize the technology to Applied Microsystems, Ltd. (AML) of Sidney, British Columbia, Canada. As of June 2000, AML manufactures and markets a product under the trade name *Spill Sentry*. *Spill Sentry* is closely based on the original Navy design.

2.2 SYSTEM DESCRIPTION

The system detects petroleum contamination in aquatic systems with an upward-looking underwater multispectral fluorometer. It is a point sensor, measuring petroleum in situ, that can be deployed in arrays to provide area coverage. The sensor's overall hardware design is intended to be rugged and inexpensive to manufacture. The sensor is shown in Figure 1. Each sensor is 20 inches tall, with a float diameter of 18 inches. The housing is primarily constructed of polyvinyl chloride with a polyethylene float. It uses the light of a pulsed xenon flash lamp to induce fluorescence in the aromatic components of free phase, dissolved phase, and emulsified petroleum hydrocarbon contamination in and on the water column. The lamp's optical output is collimated by an f/1 lens, then spectrally split by a dichroic beam splitter into visible and ultraviolet (UV) (<315nm) components that are used to excite fluorescence. The spectral separation is further enhanced by use of a custom made optical high (frequency) pass filter to achieve an extinction ratio in excess of 10^{-6}. The UV excitation light is reflected by a second dichroic beam splitter through an optical window out into the water column. The resulting fluorescence emission is collected back through the same window (180°) and directed through a series of dichroic filters for spectral separation before being measured by multiple photodetectors. A photodiode is used to monitor the UV-visible waste beam from the first beam splitter to normalize the fluorescence emission signal for pulse-to-pulse variations in lamp intensity. The output of this photodiode also serves to trigger the detection electronics. Triggering of the excitation lamp as well as analog-to-digital conversion of the photodetector output are managed by an embedded microprocessor located in the underwater housing. Data and power are transferred in one of two ways: either through a hard-wired umbilical or via a wireless data link incorporating solar power for complete autonomy. A full description of the sensor system design may be found in Andrews and Lieberman, 1998.

Fluorescence provides an extremely sensitive method allowing for accurate quantification of trace levels of hydrocarbons. The system can in principle detect all natural petroleum-based fuels and oils but does not respond to other types of oil or grease. The lower detection limit of the system has been measured to be below the U.S. Coast Guard-defined threshold for an oil spill, i.e. the appearance of visible sheen. The absolute limit of detection is unknown.

Multichannel spectral analysis allows discrimination between various classes of hydrocarbons and minimizes interference due to nonhydrocarbon fluorescence. Background fluorescence due

to the presence of POL is averaged into a baseline measurement to enable distinction between ambient “normal” POL levels or other substances providing fluoresence and an actual spill. The sensor incorporates a unique one-window optical design that makes use of the ultraviolet light energy generated by the fluorescence excitation source to prevent biofouling of the optical window, thereby enabling the sensors to remain underwater for indefinite periods of time. The sensor continuously transmits hydrocarbon data via a hard-wired or wireless link to a base station computer. The computer serves to log, process, and display data in real time; it provides automated telephonic alarming in the event of a detected spill; and it supports real-time remote data access through the Internet or intranet.

2.3 PREVIOUS TESTING OF THE TECHNOLOGY

Prior to the ESTCP effort described in this report, early prototypes of the system were tested in a limited series of studies conducted at the Ohmsett National Oil Response Test Facility in August 1997. Ultraviolet prevention of biofouling had been demonstrated for periods up to two months in San Diego Harbor between 1997 and 1998. The results of early testing are published in Andrews and Liebermann, 1998.

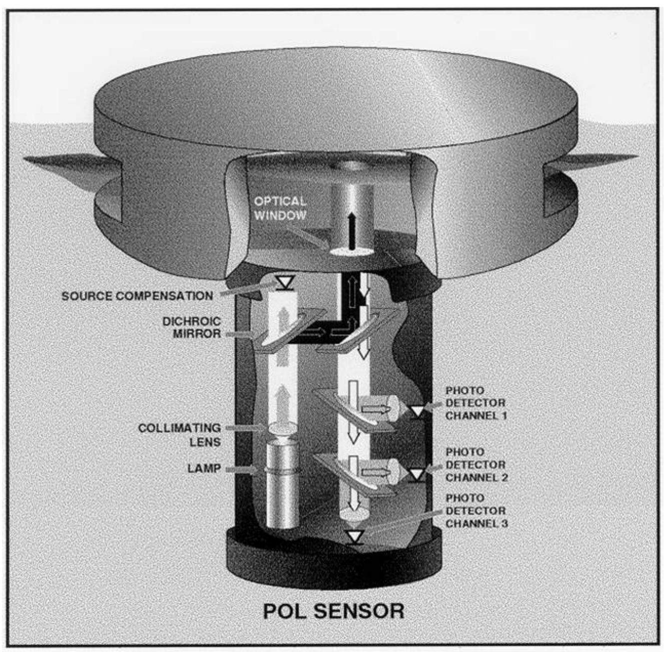

Figure 1. The Oil Spill Sensor.

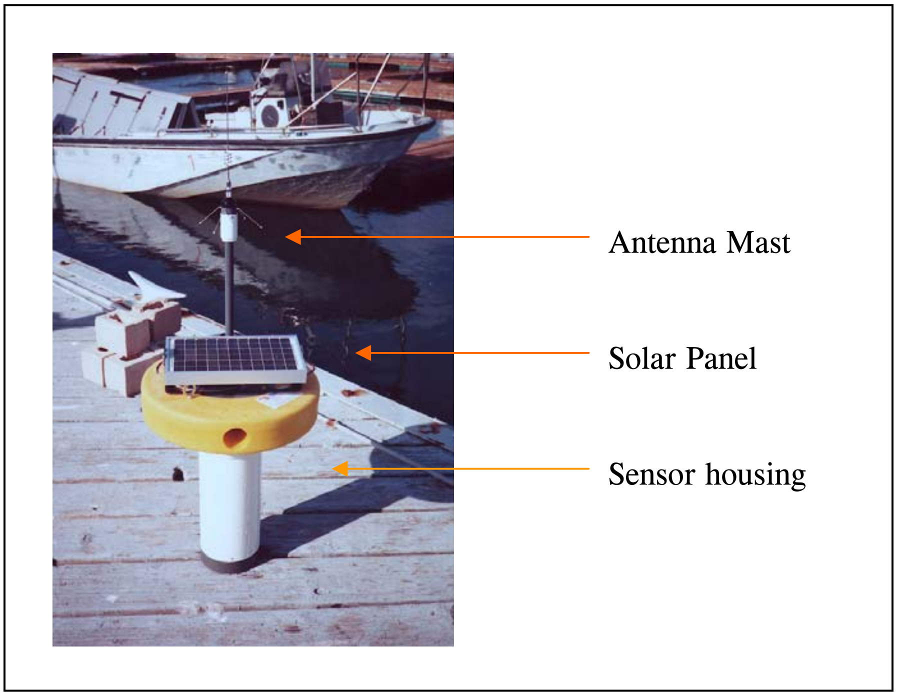

Figure 2. Wireless *Spill Sentry* Sensor.

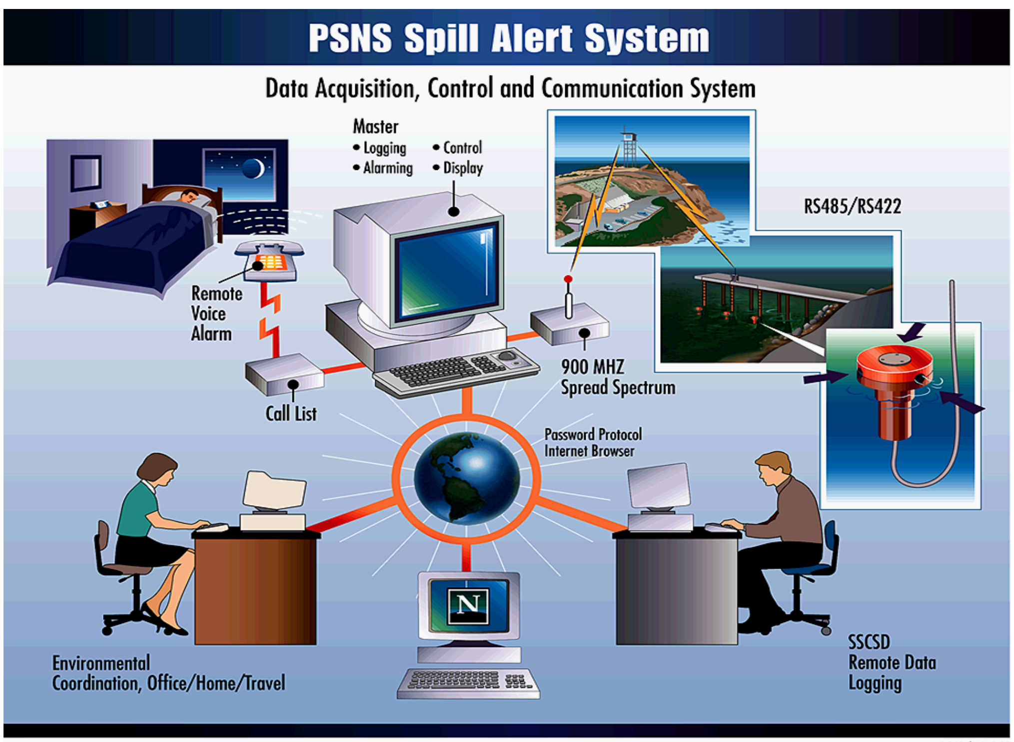

Figure 3. The Spill Alert System for Puget Sound Naval Shipyard.

2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The sensor system offers the following advantages:

1. Remote automated detection of petroleum hydrocarbons from below the water surface.

    a. This allows dissolved phase and emulsified hydrocarbons to be measured directly in the water column.
    b. By placing the sensor near the surface, floating petroleum can simultaneously be detected from below the oil-water interface. The sensor buoy maintains the sensor window at a distance of two inches from the surface at all times independent of tidal movement or limited wave action. The sensors may be kept in place by an anchor or by simply being tied off to a fixed object. However, the sensors must be moored in such a way that they do not interfere with ship traffic.
    c. Underwater deployment also provides an inherently safe means of delivering excitation energy to the sample (water). With an above water sensor, the potential exists to be in direct contact with explosive fuel vapors during a spill. High voltage electronics that trigger the excitation source (lamp) would have to be isolated in an explosion-proof housing for safety. This problem is avoided through underwater placement.

2. The optical window has been designed to remain free of biological fouling. By using an 1,800 optical geometry for the fluorescence excitation/emission-collection, the sensor requires the use of a single optical window. This may be contrasted with the more typical 900 geometry that requires the use of two windows. The advantage of a single window design is that the ultraviolet excitation light passing through the window prevents biological growth from forming. Thus, the sensor can remain underwater for indefinite periods of time. The underwater deployment duration is not limited by window fouling, which typically limits the deployment duration for other underwater optical instruments.

    One limitation of the system is that each sensor monitors a single point on the water surface directly above itself. Area coverage per sensor is entirely dependent on wind and current forces that tend to spread spills. In other words, the spill must come to the sensor. The specific number of sensors needed to cover a given area will therefore vary widely; a rough starting point may be 200 ft between sensors for continuous area coverage. Enhanced area coverage can be attained only through the use of multiple sensor arrays.

    Another limitation is that the system performance can be severely degraded in turbid water. The optically based sensors are only as effective as their ability to "see" into and through water. The sensor will no longer be effective if optical transmission through the water column drops to zero.

3.0 DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

The primary performance objectives for the *Spill Sentry* oil spill detection system are summarized in Table 1. The first objective is for the optical sensor to detect the presence of a reportable spill with 95% effectiveness or better. In other words, the sensor should be able to detect 95% of all oil spills regardless of circumstances. The next objective is for a physically robust and reliable system, one that is up and properly functioning a minimum of 99% of the time. This is a rigorous requirement but necessary for an alarm system that users can confidently rely on. Low maintenance is another objective, with the targeted level of scheduled and unscheduled maintenance being less than 2 man-hours of labor required per sensor per month. False alarms are a major concern of all users and are addressed by the next objective; the performance target for this objective is less than one per month. Finally, ease of use is the last objective; it is assessed based on subjective user feedback.

In addition to the primary performance objectives, we specified several secondary performance objectives to be evaluated. These included a background spectral interference of no more than 30% total signal intensity at any time, optical windows remaining free of bioaccumulation for at least 180 consecutive days, the ability to detect oil in up to 1-ft seas, the ability to position sensors with zero impact to operations, and the ability to spectrally discriminate between light and heavy fuel products in 90% of cases. The secondary performance objectives are summarized in Table 2. Actual performance results are discussed in Section 4.

Table 1. Primary Performance Objectives.

Type of Performance Objective	Primary Performance Criteria	Expected Performance Metric
Quantitative	Detect spills/sheen	Alarm 95% of spills
	Reliability	99% system uptime
	Maintenance	<2 man-hours/sensor/month
	Minimize false alarms	<1/month
Qualitative	Ease of use	User satisfied

3.2 SELECTING TEST SITES/FACILITIES

Demonstration sites were selected on the following basis—support of the hosting facility, availability of adequate infrastructure, history of or potential for frequent spill occurrences, and environmental or operational diversity. The spill frequency criterion was more heavily weighted due to the relative infrequency (a few times/year) of large (>1,000 gal) spills. Site selection was intended to maximize the probability that at least one large spill will occur during the finite time period of the demonstration.

Table 2. Secondary Performance Objectives.

Secondary Performance Objective	Performance Criteria	Performance Metric
Background spectral interference	Percent of discrete signal intensity attributed to factors other than the presence of POL	Spectral interference never contributing to more than 30% of total signal intensity
Window fouling	Duration of time window remains free of obscuring matter	Optical sensor window remains free of biofouling > 6 months of continuous use
Rough weather	Effectiveness in choppy seas or foul weather	Maintain effectiveness in up to 1-ft harbor chop
Deployment	Ease of deploying sensors in critical areas	Ability to deploy without interference with port operations Ability to deploy with minimal infrastructure (pier) modifications
Type discrimination	Ability to discriminate between oil/fuel products	Ability to spectrally discriminate heavy versus light POL products with 90% accuracy (correct classification of *heavy* or *light* in nine out of 10 cases)

Controlled testing was performed at the Department of the Interior's Ohmsett test facility in New Jersey. Ohmsett provides a large wave tank dedicated to the test and evaluation of oil spill detection and response equipment. It enables key quantitative tests to be performed in a controlled environment without having to wait for a random spill event as at the demonstration sites.

3.3 TEST SITE CHARACTERISTICS AND HISTORY

Along with Ohmsett, four active DoD facilities were selected to host concurrent demos. At each facility, sensor locations were determined through consultation with local responders and authorities. A brief description of each follows.

3.3.1 Ohmsett Test Facility

Ohmsett is located at the Naval Weapons Station Earle Waterfront in scenic Leonardo, New Jersey (approximately one hour south of New York City). This test facility is managed by the Department of Interior's Minerals Management Service in cooperation with the U.S. Navy, the U.S. Coast Guard, and the Environmental Protection Agency. The large, outdoor, aboveground concrete test tank measures 203 m long by 20 m wide by 3.4 m deep (Figure 4). The tank is filled with 2.6 million gal of clear saltwater. The Ohmsett test tank allows testing of full-scale equipment. The tank's wave generator creates realistic sea environments, while state-of-the-art data collection and video systems record test results.

Through a variety of mechanical, electrical, and chemical systems at Ohmsett, the following test parameters can be controlled or measured:

- Sea state (wave height, length, and period)
- Meteorological data
- Water temperature and salinity
- Volume of oil encountered and recovered by test equipment or protocol
- Oil-water ratios
- Physical characteristics of experimental oil
- Behavior of treated oils

The Ohmsett facility was used to conduct controlled tests to determine the sensor's sensitivity to a series of different petroleum products at various sea states.

Figure 4. Ohmsett Test Facility.

3.3.2 Langley Air Force Base

Langley Air Force Base in Hampton, Virginia, is among the oldest continuously active air bases in the United States. The facility is home to the 1st Fighter Wing flying the F-15 Eagle. Covering 2,900 acres, Langley Air Force Base is located on a peninsula in the southwest part of the lower Chesapeake Bay. Hampton is near Newport News and Poquoson.

A single sensor was placed along the lone fuel pier at Langley. The spill history of the site is unknown as the facility does not keep written records of spill events. The site was selected primarily because the demonstration could be logistically supported at very small additional cost to the concurrent and nearby Norfolk demonstration, and because it provides an opportunity to test the system in an estuary and in an Air Force operational environment. The sensor positioning did not hinder ship movement or fueling operations.

3.3.3 Naval Station Norfolk

Naval Station Norfolk, Virginia, occupies about 3,400 acres in the northwest portion of Norfolk and is the world's largest naval station. The naval station is home port to aircraft carriers, cruisers, destroyers, large amphibious ships, submarines, a variety of supply and logistics ships, C-2, C-9, C-12, and E-2 fixed-wing aircraft and H-3, H-46, H-53, and H-60 helicopters. Norfolk, with its 14 piers, is homeport to 78 ships. Port Services controls more than 3,100 ships' movements annually as they arrive and depart their berths. Port facilities extend more than four miles along the Hampton Roads waterfront and include some seven miles of pier and wharf space.

Three wireless sensors were installed at Norfolk. Two sensors were located along the waterfront piers with an additional sensor to be located at the Bousche Creek Outfall of Willoughby Bay. The site was selected because of its history of frequent large spills (>1,000 gal) which have occurred at a rate of 2-3 per year over the past decade. The specific locations were selected because the ships are refueled pier-side from fuel barges or litters. The sensors were positioned so that they would not interfere with ship movement or waterfront operations. The base station was established at the Port Operations center near the waterfront. The sensor locations are graphically depicted in Figure 5.

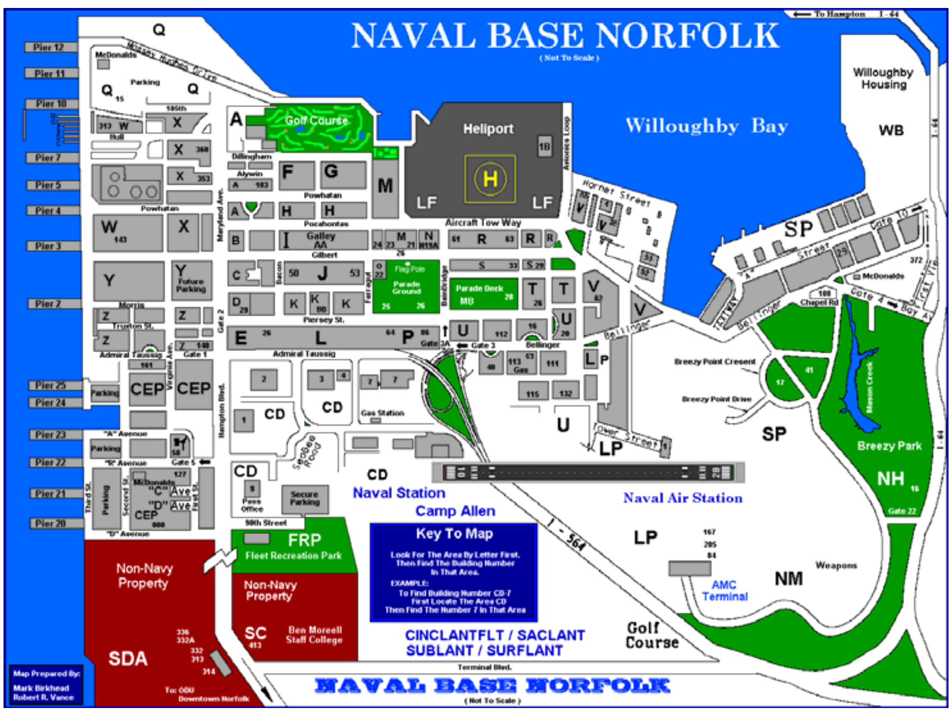

Figure 5. Location of *Spill Sentry* Sensors at Naval Station Norfolk.
Sensor and base-station locations are shown as green stars.

3.3.4 Puget Sound Naval Shipyard

Puget Sound Naval Shipyard (PSNSY) in Bremerton, Washington, was originally established in 1891 as a naval station and was designated Navy Yard Puget Sound in 1901. Approximately 30% of the Shipyard's current workload involves inactivation, reactor compartment disposal, and recycling of ships. PSNSY is the Pacific Northwest's largest naval shore facility and one of Washington State's largest industrial installations. It is also the largest shipyard on the West Coast, employing approximately 7,700 people.

Four hard-wired sensors were installed at the shipyard, all along Pier B. The site was selected primarily because of its relatively frequent occurrence of large spills (>1/yr). The sensors do not interfere with ship movement or pier side operations. The hard-wired sensors communicate directly with a radio transceiver located near the pier. Data is then transmitted over a wireless data link to the base station computer located approximately 500 meters away on the third floor of the Fleet Industrial Supply Center (FISC) building.

3.3.5 Naval Station Pearl Harbor

Naval Station Pearl Harbor, Hawaii, supports 50 home ported fleet units and 24 submarines. The station currently occupies and maintains 1,107 acres of land throughout the Pearl Harbor complex, ranging from Waipio Peninsula to Bishop Point and including Ford Island. Operating the Navy's busiest harbor, Naval Station Pearl Harbor annually completes 65,000 boat runs and transports 2.4 million passengers and 200,000 vehicles to and from Ford Island and other harbor locations. Navy-manned *USS Arizona* tour boats transport nearly 2 million visitors to the memorial each year.

Four wireless sensors were installed at Pearl Harbor (Figure 6). The sensors were located near the Arizona Memorial, and at piers H2/3, M2/3, and B17. The base station was located at the OSOT oil spill response center on Ford Island. The site was selected primarily because of its history of relatively frequent large spills (>1/year) and for the opportunity to test the sensors in a diverse biofouling environment. The sensors' positioning did not interfere with ship traffic or pier side operations.

Arizona Memorial

Pier H2

Pier B17

Pier M2

Figure 6. *Spill Sentry* Sensor Locations at Pearl Harbor.

3.4 PHYSICAL SETUP AND OPERATION

The installed equipment consists of floating *Spill Sentry* oil-spill sensors, a data-logging base-station computer/web-server, and a wireless spread spectrum FM radio connection between the base station and sensors. The sensors were moored at the deployment location; either tied directly to the pier structure or an anchor. The base station required a local area network connection to support Internet capabilities or, as an alternative, a dial-up connection through a local phone line. The base station also required a separate telephone connection to support telephonic alarming. The wireless data link operates at 900 MHz, a frequency and power that does not require Federal Communications Commission (FCC) licensing; and as it frequency-hops, it does not interfere with any wireless local transmissions. Repeaters or special directional antennas were not used.

4.0 PERFORMANCE ASSESSMENT

4.1 PERFORMANCE DATA

4.1.1 Signal-to-Noise Ratio

The primary purpose of controlled testing at the Ohmsett facility was to quantify sensor response to petroleum under wave conditions ranging from quiescent to a 1.5-ft simulated harbor chop. The quiescent response to three types of petroleum is displayed in Table 3. The data represent sensor *Spill Sentry* response to 200 ml of product spilled into a 160-sq ft area. The sensor detected (S/N <2) each type of petroleum tested under all wave conditions up to the tested maximum of 1.5-ft wave height.

Table 3. Sensor Response (S/N) to 0.2 Liters of Petroleum Spilled onto a 160-sq ft Area of Calm Water.

Area	Gasoline	Lube Oil	Diesel Fuel
Channel 1 (>450 nm)	11	2.9	7.8
Channel 2 (400-450 nm)	11	2.9	5.0
Channel 3 (320-400 nm)	5.1	4.9	12.7

4.1.2 Wave Height Effects

The correlation between sensor readings for each of the three channels and wave height under simulated choppy conditions is displayed in Table 4. The results indicate a very weak negative correlation between the sensor response and wave height. The negative sign of the correlation is attributable to the back-reflection effect. The small magnitude of the correlation, particularly for Channel 3, is evidence that the sensor response is significantly independent of surface motion and that surface waves will not generally produce a false response or alarm. Sensor response versus wave height is plotted in Figure 7. From the figure it can be seen that there is very little correlation between wave height and sensor response. The range of response values is larger at smaller wave heights. This may indicate an effect on response up to a threshold wave height after which the response is essentially decoupled from surface interactions.

Table 4. Correlation Between Optical Signal and Wave Height.

Channel	CH 1	CH 2	CH 3
Correlation (r)	-.43	-.35	-.09
Shared variance (r^2)	.19	.13	.01

4.1.3 Petroleum Products Differentials

The *Spill Sentry* system has the potential to distinguish between different petroleum products by utilizing the information contained in all three optical channels. Typically this is done by comparing the response ratios of the channels. Lighter products and dissolved phase constituents will have a stronger response in the UV corresponding to Channel 2. Heavier products will cause a response in Channel 3 while also causing an increased response in the blue spectral region measured by Channel 2. Channel 1 is expected to show an increase in response to nonpetroleum fluorophores such as chlorophyll or for solid material or debris that reflects light directly back into the sensor. The Channel 1 response can be used to distinguish false positives from actual spills. Figures 8 and 9 show the discrimination results from the Ohmsett testing. Crude oil, the heaviest of the products tested, is the only material causing a significant increase in the Channel 2 to Channel 1 response ratio. Fluoroscene, the non-oil, is the only product yielding a significantly reduced Channel 2 to Channel 1 ratio. The variation among the other petroleum products is mostly contained within the Channel 2-3 ratio. The separation in Figure 9 would indicate that the separate products could be distinguished under ideal circumstances. However, as seen in the previous tests, the channel response ratios can change depending on surface activity (back-reflection effect). This was an unexpected finding and the channel ratios were not originally tested under wave conditions for each of the products. As a result, while it appears that the *Spill Sentry* system can distinguish between different fuel products, it is still unknown whether the variance in channel ratios due to wave action would impact these results.

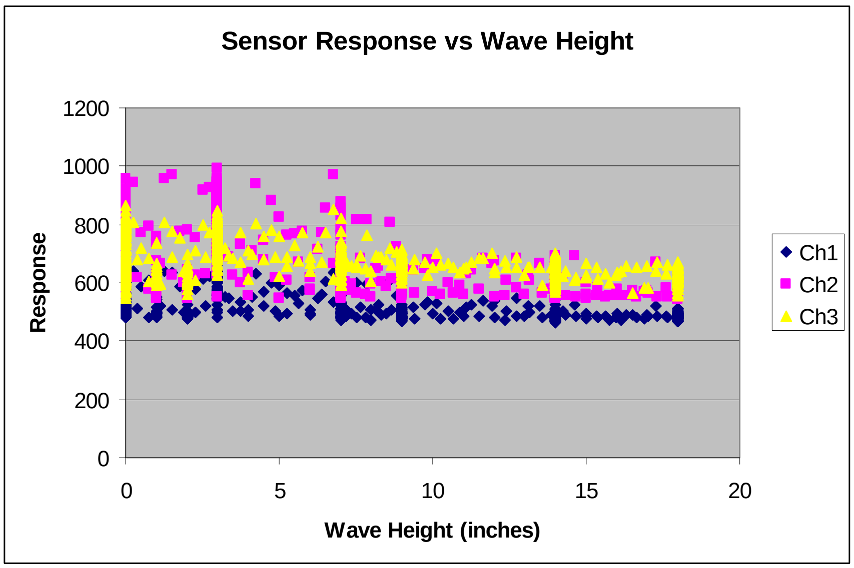

Figure 7. Sensor Response Versus Wave Height.

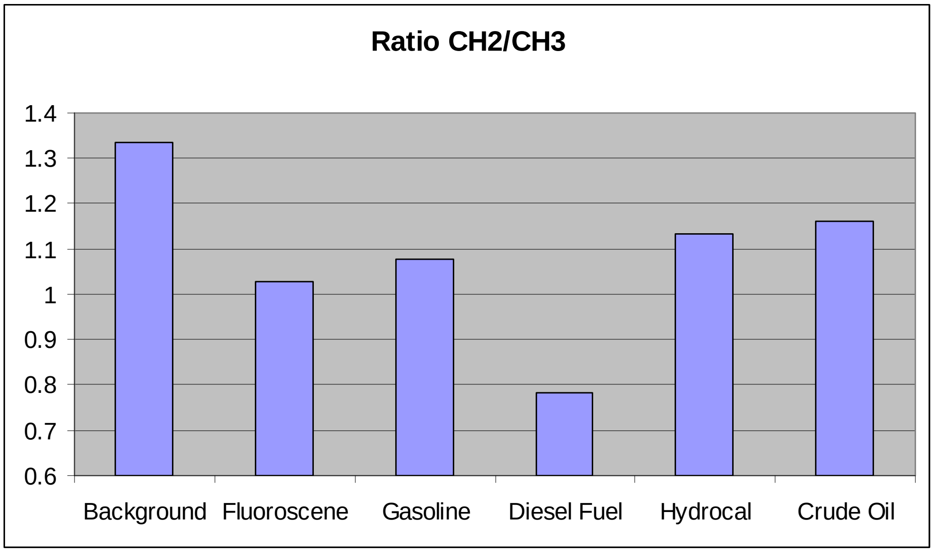

Figure 8. Ratio of Channel 2 to Channel 3.

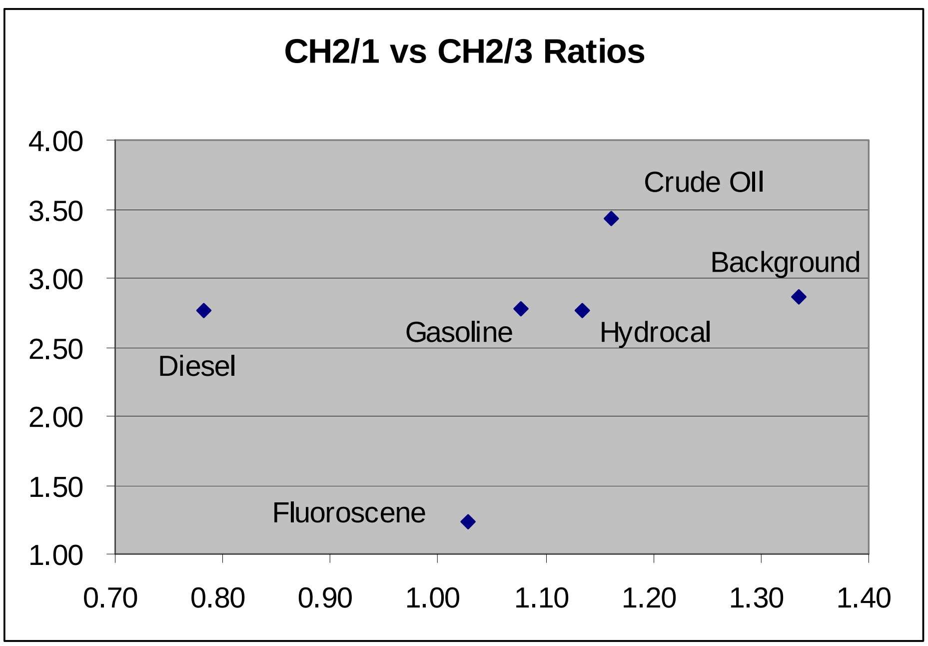

Figure 9. Channel 2/1 Ratio Plotted Against the Channel 2/3 Ratio.

4.1.4 Lens Biofouling

Of critical concern prior to field testing was whether an underwater optical system could perform effectively for extended periods of time without becoming fouled. The use of UV light as a germicide to prevent window fouling had never before been reported. In the end, the method proved highly effective in preventing the accumulation of window biofouling at each of the

demonstration sites. This unique application of an optical method for the prevention of underwater biofouling has potential application in many other underwater technologies. An example of fouling prevention is presented in Figure 10.

Figure 10. Fouling Around Optical Window.

4.1.5 False Alarms

For the purposes of this report, a false alarm is any event that triggers a *Spill Sentry* alarm when a petroleum spill has not actually occurred. During the demonstrations, false alarms did occur; however, the false alarm rate due to a nonpetroleum substance or signal error was zero. All false alarms were caused by setting the sensor alarm threshold too low, thereby allowing high background levels to trigger an alarm. However, the false alarm rate during the demonstration tests significantly exceeded the target objective of less than one false alarm per month. The actual average false alarm rate is shown in Table 5. The alarm rate could be dramatically reduced by simply raising the alarm threshold to four standard deviations or higher.

Table 5. Monthly Average False Alarm Rate at Each Demonstration Site.

	PSNS	Norfolk	Langley	Pearl
Two standard deviations threshold	16	9	11	7
Three standard deviations threshold	1.1	0.8	N/A	1.2

4.1.6 Reliability

Spill Sentry system reliability was evaluated separately for the sensor itself, the network and computer system, and the communication system. Overall, the system fell well short of meeting the 99% uptime reliability objective. A substantial amount of downtime can be attributed to network reliability, radio frequency interference, and physical storm damage to the in-water sensors. Many of these effects were a result of inexperience from having never before deployed

the system in a extended field environment. Lessons learned from the demonstrations will directly lead to significantly improved system reliability in future deployments. System downtime is shown in Table 6.

Table 6. Percentage of System Downtime.

	PSNS	Norfolk	Langley	Pearl
Network down (does not affect alarming)	21%	8%	0%	0%
Telephone line problem (affects alarming)	0%	12%	52%	37%
Radio transmission problem (interference)	3%	37%	0%	0%
Sensor damaged	23%	25%	4%	8%
Other	6%	11%	10%	7%
Total downtime (some problems concurrent)	35%	50%	56%	46%

4.2 PERFORMANCE CRITERIA

The general performance criteria used to evaluate system performance are tabulated in Tables 7 and 8.

Table 7. Primary Performance Objectives with Results.

Type of Performance Objective	Primary Performance Criteria	Expected Performance Metric	Actual Performance Objective Met?
Quantitative	Detect spills/sheen	Alarm 95% of spills	Yes
	Reliability	99% system uptime	No
	Maintenance	< 2 man-hours/sensor/month	Yes
	Minimize false alarms	< 1/month	No
Qualitative	Ease of use	User satisfied	Yes

Table 8. Secondary Performance Objectives with Results.

Secondary Performance Objective	Performance Criteria	Performance Metric	Objective Met?
Background spectral interference	Percent of discrete signal intensity attributed to factors other than the presence of POL	Spectral interference never contributing to more than 30% of total signal intensity	Yes
Window fouling	Duration of time window remains free of obscuring matter	Optical sensor window remains free of biofouling > 6 months of continuous use	Yes
Rough weather	Effectiveness in choppy seas or foul weather	Maintain effectiveness in up to 1-ft harbor chop	Yes
Locating	Ease of deploying sensors in critical areas	Ability to deploy without interference with port operations Ability to deploy with minimal infrastructure (pier) modifications	Yes
Type discrimination	Ability to discriminate between oil/fuel products	Ability to spectrally discriminate heavy versus light POL products with 90% accuracy (correct classification of *heavy* or *light* in nine out of 10 cases)	Inconclusive

4.3 DATA ASSESSMENT

Overall the *Spill Sentry* met or exceeded expectations in most key performance objectives but significantly underperformed in two critical areas: reliability and false alarm rate. The system easily detected all types of petroleum tested, performed well in quiescent as well as choppy conditions, and was unaffected by biofouling. The relatively high false alarm rate can be substantially improved by adjusting the alarm threshold to meet site conditions and user needs. The reliability of system, as measured by uptime during the demonstrations, averaged just 47%. This is attributable to the lack of experience using and maintaining the prototype system. Lessons learned during the demonstrations as well as engineering improvements made to production systems are expected to dramatically improve future performance in this area.

4.4 TECHNOLOGY COMPARISON

The existing process for the *Spill Sentry* is human observation and reporting. Because of the infrequent nature of oil spills, there are not currently enough data to statistically compare the two methods. Additionally, *Spill Sentry* will most likely find application in augmenting human observation rather than by entirely replacing it. As addressed in previous sections, employing an automated spill detection system has distinct advantages over reliance on human observation alone; it will ultimately be up to the user or regulators to decide whether the added benefits are cost effective in any given application.

One of the distinct advantages is that the *Spill Sentry* is a 24/7 sensor while human observation is limited to daylight hours. This will allow fueling operations during nighttime hours in order to meet military operational needs.

5.0 COST ASSESSMENT

5.1 COST REPORTING

Table 9 shows the system costs associated with the oil spill sensor technology.

Table 9. Technology Costs by Category.

Direct Environmental Activity Costs		Indirect Environmental Costs	Other Costs and Benefits
Start-up	**Operation and Maintenance**		
Activity	**Activity**	**Activity**	**Activity**
Capital equipment	Operator labor	Compliance audits	Mission readiness
Equipment mods	Utilities	Document maintenance	Public image
Site preparation	Consumables (e.g., lamps x 2/yr)	Reporting requirements	Cost avoidance -Liability -Cleanup
Installation	Equipment maintenance		
User training			

Costs were identified separately for each of the four demonstration sites and extrapolated to estimate the average cost of implementation at a new site. There is no existing oil spill detection technology or methodology with which to compare costs directly; instead, a comparison will be made based on the avoided cost due to rapid response. No cost assessment was done for the Ohmsett tests as the tests at this site were for sensor assessment only.

5.1.1 Direct Costs

The direct costs are calculated or defined as follows:

- *Capital equipment* includes durable components that are purchased at start-up, including in-water sensors, radio transceivers, antennas, masts, permanent cabling, computer equipment, solar panels, and any other major system component or end item.

- *Equipment modifications* include engineering and material costs necessary to modify the *Spill Sentry* system to meet local user requirements.

- *Site preparation* covers the cost of any required changes to the local infrastructure to support the *Spill Sentry* installation. This may include, for example, installation of conduit for cabling, fabrication of mooring support system, or physical modification to a pier.

- *Installation costs* are determined by the number of man-hours required for complete system installation, including Space and Naval Warfare Systems Command (SPAWAR) technicians and local user support. When unknown,

technician man-hour costs are estimated at $75/hr. This category also includes travel costs and time to the demonstration site from SPAWAR San Diego.

- *User training cost* is estimated as the number of user man-hours spent in *Spill Sentry* meetings or briefings during start-up. When unknown, user man-hour cost is estimated at $75/hr. SPAWAR does not currently provide a formal user training program for *Spill Sentry*. Training is provided informally on an as-needed basis.

- *Operator labor cost* is estimated as the number of user man-hours times the labor cost required to maintain or interact with the *Spill Sentry* system during the year.

- *Utilities* represent the cost of electrical power to operate the *Spill Sentry* system. This typically includes the base station computer, a 1-watt transceiver, and spill sensors if not solar powered. Electricity costs are estimated at $0.10 per kilowatt-hour for each site.

- *Consumables* include nondurable items that require replacement on a yearly basis or sooner. This may include line and hardware for mooring as well as flashlamps and batteries for the sensors.

- *Equipment maintenance* is calculated as the sum of all costs related to maintaining the *Spill Sentry* system in operable condition. These costs include labor, travel, materials, and equipment usage (e.g., boats).

5.1.2 Indirect Costs

Indirect costs include *compliance audits, document maintenance, and reporting requiremen*ts. However reporting requirements are the same with or without the *Spill Sentry* system. All spills must be reported and there is therefore no net impact to cost. Compliance audits were not required at any of the demonstration sites during this study, so again there is no impact to overall cost. Document maintenance is not required per se; however, the modest costs associated with maintaining the sensor data in the base station data base will be included in this category based on the man-hours dedicated to this purpose.

5.1.3 Other Costs and Benefits

The *other costs and benefits* category includes items that are very difficult to accurately quantify but nevertheless have a tangible impact to the organization. These include:

- *Mission readiness.* There is a strong potential for the *Spill Sentry* system to enhance mission readiness by allowing oily waste transfers in port to be performed at night. Current practice generally limits fuel transfers to daylight hours because of the difficulty of visually identifying a spill during darkness. The operational window for these types of activities could double if secure nighttime transfers could be enabled.

- *Public image*. This is another indirect benefit that is difficult to quantify in any meaningful way, but the benefits are very tangible. An example will serve to illustrate the point. During the *Spill Sentry* sensor installation at PSNSY, local news covered the "event" portraying the shipyard as being proactive in its attempts to minimize risk and potential environmental damage to the local waterways. This was the first positive publicity after several years of stories about the real and potential negative ecological impact due to shipyard activities.

- *Cost avoidance — liability and cleanup.* This is the primary cost benefit to automated spill detection. Early response can lead to reduced spill volume and lower cleanup costs. The type of spill event that would derive the most benefit from *Spill Sentry* occurs once every yr or two at most facilities. This is a prolonged spill that begins at night or during the weekend and is not reported for many hours before a response is initiated. During the demonstration, there were no actual spills of this type detected by the system. Cost savings in this category will therefore be estimated from spill statistics. It is of interest to note that there was one opportunity to detect a spill at Norfolk within the first weeks after installation. A prolonged spill of at least hundreds of gals of fuel occurred very near one of the sensors on the weekend before a presidential visit to the site. The spill was not detected for more than 24 hrs before a response team was mobilized to clean up the spill. The *Spill Sentry* system failed in this instance because of high-power radio wave interference with the wireless data path. The cause is still unknown but likely due to the use or testing of shipboard radio frequency equipment, perhaps radar, in close proximity to the base station radio antenna. The radio interference problem was resolved during the next maintenance visit but the opportunity was lost.

5.2 COST ANALYSIS

Anticipated *Spill Sentry* life-cycle costs can be estimated from the demonstration deployment expenditures. A detailed breakdown of specific direct costs associated with each of the four demonstration sites is described in the ESTCP Final Report. Operation and maintenance costs are estimated to be somewhat lower than experienced during the demonstrations because the sensors will in most cases be serviced locally or, when necessary, shipped for repair; hence, significantly smaller travel costs will be involved. The start-up costs can be expected to be similar to the demonstration costs for wireless system installations.

The time period used for calculating the life-cycle cost is obviously a critical part of the calculation. A conservative estimate of a 5-yr service life for the system will be used for this example. After 5 yrs the computer base station may need to be updated, and an estimated one half of the in-water sensors at a given site may have been damaged beyond repair due to storms or other mishaps. The radio systems, a small fraction of the total system cost, will probably still have several years of useful service remaining after 5 yrs. This example will be based on a four-sensor wireless installation. The future value of money is ignored for these calculations. Estimated cost for equipment replacement is $12,400.

The facility capital cost, site modifications necessary to accommodate *Spill Sentry* implementation, will vary but might typically include installation of a phone line and an Ethernet hook-up if neither is already available for the base station computer. Estimated cost is $200.

Start-up costs can be estimated directly from the start-up costs associated with the four-sensor installation performed for the Pearl Harbor demonstration. Estimated cost is $56,600.

Operations and maintenance costs over the 5-yr life will be estimated assuming two sensor repairs per yr, annual lamp and battery replacement for each sensor, and two man-hours per sensor per month maintenance and cleaning. Labor costs are estimated at $40/hr. The use of a boat crew is added in assuming twice yearly use, 2 hr each time.

Operator labor (60 mo x 8 hr/mo x $40/hr)	$19,200
Utilities (base station, 250 watts)	$1,095
Consumables (line, floats, etc.)	$250
Sensor repair (2/yr at $300 each case)	$3,000
Routine maintenance (parts, $400/sensor/yr)	$8,000
Boat crew (semiannually)	$4,000
Total 5-Yr Operation and Maintenance Cost	**$35,545**

The total 5-yr life-cycle cost is estimated as the sum of the individual costs listed above. This cost is tabulated in Table 10.

Table 10. *Spill Sentry* 5-Yr Life-Cycle Cost.

Item	Cost
Facility capital cost	$200
Start-up cost	$56,600
Operation and maintenance cost	$35,545
Demobilization cost	$200
Equipment replacement cost	$12,400
Total 5-Yr life-cycle cost	**$104,945**

5.3 COST COMPARISON

The cost of oil spill cleanup in port can vary widely. Factors that influence cleanup costs include:

- Type of product spilled
- Location of the spill
- Timing of the spill
- Size of the spill
- Cleanup techniques employed
- Weather conditions
- Sensitive areas affected
- Local laws and regulations

Etkin cites numerous case studies of oil spills in port with cleanup costs that range from a low of \$2.33 per gal to \$1,125.42 per gal. There are two key factors in reducing the impact, and ultimately the cost, of an oil spill in port. First is preparedness, having the appropriate personnel and resources ready to respond. The second is rapid response; it is generally agreed that timely response is essential in minimizing cleanup costs.

Filadelfo has analyzed the cost of in-port spills at Naval Station San Diego and reports similar estimates. Of nine case studies, the cost/gal ranged from a low of \$5 to a high of \$1,900 per gal. The mean was \$536/gal.

The Center for Naval Analysis has identified specific costs associated with Navy oil spills in port. These include both variable and fixed costs. Variable costs include those expenses directly attributable to a specific spill event and are usually proportional to spill frequency and volume. These would include, for example, labor costs, contract costs, federal and local fines, the value of lost product, and the use of consumables. Fixed costs are those that are incurred whether or not a spill occurs. Examples include spill response training, infrastructure costs, and contingency plan preparation.

A cost comparison between the *Spill Sentry* technology and the current method (visual observation) for detecting spills in port must take into account the cost of implementing and maintaining each approach as well as the potential cost savings from reduced cleanup expense. As for implementation and maintenance costs, the currently employed method of visual observation, along with its associated costs, would in all likelihood continue unchanged, even if the *Spill Sentry* system were adopted for use. The relative cost of the current method is \$0; hence, adoption of *Spill Sentry* will provide no reduction in the cost of implementing passive visual observation. Any cost benefit from *Spill Sentry* must come from a reduction in cleanup cost relative to system fielding expenses.

It is impossible to accurately estimate the volume of spilled oil that can be avoided by using the *Spill Sentry* system. Statistics are thin and conditions vary greatly. Early detection may have little impact on small spills; *Spill Sentry* will earn its keep by minimizing the volume and impact of large spills, leaking pipes, or overflowing tanks that can be stopped and contained more quickly through immediate detection. But those events occur relatively infrequently. The approach to cost analysis taken here is to estimate the cost of implementing and maintaining a *Spill Sentry* system in comparison to the average or potential cost of a large oil spill. Then, estimate the number or size of an avoided spill necessary to reach a break-even point. The potential end user or risk manager can then decide whether *Spill Sentry* implementation at his or her specific location makes economic sense.

The potential cost avoidance provided by the *Spill Sentry* system would come by way of a reduction in federal, state, and local fines, including Natural Resource Damage Assessments (NRDA), avoided loss of petroleum, lower cleanup costs (rapid response), ability to conduct 24-hr port operations, and perhaps even a reduction in the cost of having a required visual watch.

In terms of spill prevention (minimization), the *Spill Sentry* system could pay for itself by reducing the volume of a single spill by as little as 200 gal. Using the average cleanup cost of

$536/gal cited above, along with the 5-yr *Spill Sentry* cost estimate of nearly $105,000.00, the system could pay for itself by preventing 196 gal from accidentally being released into the environment over a 5-yr service life.

6.0 IMPLEMENTATION ISSUES

6.1 COST OBSERVATIONS

The relative breakdown of system costs is shown in Figure 11. Start-up costs for the system represent more than 50% of the total estimated 5-yr life-cycle cost. This includes an investment in base station hardware, telemetry equipment, and the sensors themselves. Maintenance costs are responsible for one-third of total estimated costs. At this time, the only foreseeable way to reduce start-up costs is through increased production efficiencies, for example, through economies of scale as the system gains wider acceptance and use. Maintenance costs can potentially be reduced in the near term as system reliability improves.

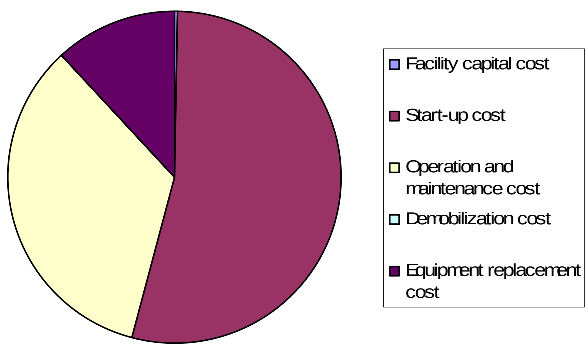

Figure 11. 5-Yr Life-Cycle Cost for an Installed Four-Sensor *Spill Sentry* System.

6.2 PERFORMANCE OBSERVATIONS

In terms of technical performance, i.e. accurately detecting spilled oil under a variety of conditions, the *Spill Sentry* generally met or surpassed objectives. The one significant area where the *Spill Sentry* prototype sensor performed poorly was reliability. This is in large part attributable to the fact that it was a first generation model and technicians responsible for installing and maintaining the systems were themselves learning as the project preceded. Building on lessons learned, future deployments can be expected to have substantially fewer reliability issues.

6.3 SCALE-UP

The *Spill Sentry* system can, in principle, be scaled up to any arbitrary number of sensors. The only potential constraint is the availability of bandwidth for data transmission from the in-water buoys to the base station. For example, an FM radio-based buoy network in which each sensor transmits a 1-second burst of data every 3 minutes over a single channel would be limited to a theoretical maximum of 180 total sensors. In practice, the actual number of sensors that could be deployed for a given bandwidth is something less than the theoretical maximum; however, bandwidth can always be expanded by increasing the number of communication channels so that having too many sensors should never be an issue.

6.4 OTHER SIGNIFICANT ISSUES

The *Spill Sentry* oil spill detection technology was transitioned to the private sector during the first year of the ESTCP validation effort. The sensors used in the Norfolk, Langley, and Hawaii deployments were in fact early production prototypes manufactured by commercial transition partner Applied Microsystems Ltd. (AML, Sidney, British Columiba). The U.S. Navy assigned exclusive rights to manufacture and market the *Spill Sentry* technology to AML in exchange for an initial licensing fee and royalties on all future sales of *Spill Sentry* systems worldwide. In addition, the U.S. federal government receives discounted pricing for *Spill Sentry* systems purchased for government use and activities. AML has sold *Spill Sentry* systems worldwide and continues to manufacture and market the systems. Additional information on the AML *Spill Sentry* can be found on the Internet at:

http://www.appliedmicrosystems.com/sensors/oil-on-water.html

The SPAWARSYSCEN *Spill Sentry* technology transfer effort has led to receipt of the Federal Laboratory Consortium 2001 Award for Excellence in Technology Transfer. In addition to the commercial transition, the *Spill Sentry* oil spill detection system has been adapted to other military and commercial uses by incorporating additional sensing technology onto the sensor platform. A modified version the *Spill Sentry* has recently been deployed in the Persian Gulf by the U.S. Navy Meteorological and Oceanographic Command for collecting bioluminescence and optical transmission data as well as oil spill (fluorescence) data in Manama Harbor. Other DoD agencies have also purchased modified sensors for military applications.

6.5 LESSONS LEARNED

There were a significant number of important lessons learned during this demonstration and evaluation period. All have been passed on to AML for improving system design and operation. Most have resulted in modifications or improvements to the spill detection system that makes it a much more reliable system than the one first deployed for these demonstrations. Improvements taken directly from demonstration experiences include:

- Use of a timed auto-reboot to limit base station computer down time
- Use of repeaters and high gain antennas to improve radio communication
- Incorporation of satellite-based communication for remote areas
- Protective sensor housing to improve survivability
- Improved mooring and anchoring methods for survivability
- Improved maintenance process involving shipment of damaged sensors
- Easier to interpret user interface

6.6 END-USER ISSUES

End users can now obtain *Spill Sentry* systems, system service, and support directly through AML. The technology currently being marketed by AML has benefited significantly from the lessons learned from the ESTCP demonstrations. The newest generation of sensors has been significantly improved to be more durable, less expensive, and easier to deploy. Nevertheless, several user concerns still remain, including concern about system sensor survivability during

severe storms. Additional planned demonstrations, system deployments undertaken by early adopters, and the incorporation of evolutionary engineering improvements will eventually provide the basis and track record for mainstream users to decide whether or not to employ automated spill detection at their local facility.

6.7 APPROACH TO REGULATORY COMPLIANCE AND ACCEPTANCE

No permits or licenses are required to deploy the *Spill Sentry* technology.

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APPENDIX A

POINTS OF CONTACT

Point of Contact	Organization	Phone Fax E-mail	Role
John Andrews	SSC-SD D361 53475 Strothe Road San Diego, CA 92152-6325	Phone : 619-553-2769 Fax : 619-553-2876 E-Mail : jandrews@spawar.navy.mil	PI
Stephen Lieberman	SSC-SD D361 53475 Strothe Road San Diego, CA 92152-6325	Phone : 619-553-2778 Fax : 619-553-2876 E-Mail : lieberman@spawar.navy.mil	Co-PI
Greg Anderson	SSC-SD D362 San Diego, CA	Phone: 619-553-1618 E-Mail: Greg.anderson@navy.mil	Lead Engineer
William Boucher	Puget Sound Naval Shipyard	Phone: 360-476-1842 E-Mail: boucherw@psns.navy.mil	Lead, PSNS Demo
Lisa Swann	Langley Air Force Base	Phone: 757-764-1130 E-Mail: Karen.Barta@langley.af.mil	Lead, Langley Demo
Maureen Connors	Navy Public Works Center 9742 Maryland Avenue Suite 211 Norfolk, VA 23511-2797	Phone : 757-444-3009, Ext. 385 E-Mail : mconnors@pwcnorve.navy.mil	Lead, Norfolk Demo
Cynthia Pang	Navy Region Hawaii Code 01ERM 517 Russell Avenue, Suite 110 Pearl Harbor, HI 96860-4884	Phone : 808-473-4689 Fax: 808-473-2870 E-Mail : pangcy@hawaii.navy.mil	Lead, Pearl Demo
Bill Schmidt	Ohmsett Box 473 Atlantic Highlands, NJ 07716	Phone: 732-866-7183 Fax: 732-866-7189	Ohmsett Program Manager
Lora Kear (Computer Sciences Corporation)	SSC-SD D361 53475 Strothe Road San Diego, CA 92152-6325	Phone : 619-553-2761 Fax : 619-553-2876 E-Mail : kear@spawar.navy.mil	Data QA/QC Coordinator
Robert Haydock	Applied Microsystems Ltd. 2071 Malview Avenue Sidney, B.C. Canada V8L 5X6	Phone: 250-656-0771 Fax: 250-655-3655 E-Mail: robert@appliedmicrosystems.com	Commercial Partner Patent Licensee

ESTCP Program Office

901 North Stuart Street
Suite 303
Arlington, Virginia 22203

(703) 696-2117 (Phone)
(703) 696-2114 (Fax)

e-mail: estcp@estcp.org
www.estcp.org